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A Dynamic Mechanical Model for Hand Force in Right Angle Nutrunner Operation

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A deterministic mechanical model based on physical tool parameters was used for estimating static and dynamic hand forces from kinematic measurements. We investigated the effects of target torque (25, 40, and 55 Nm) and threaded fastener joint hardness (35-, 150-, 300-, 500-, and 900-ms torque buildup time) on hand force. Estimated hand force was affected by target torque and joint hardness. Peak and average dynamic hand force was least for the hard joint (35-ms buildup) and greatest for the medium hardness joint (150-ms buildup). Tool inertia played the major role in reducing hand reaction force. Estimated hand force decreased when the inertial force component increased. Inertial force decreased by 366% when buildup time increased from 35 to 300 ms. Static modeling overestimated hand force; the error ranged from 10% for a soft joint to 40% for a hard joint. Results from direct hand force measurements using a strain gauge dynamometer showed that the dynamic model overestimated peak hand force by 9%. However, average hand force and force impulse were not significantly overestimated.

INTRODUCTION

Power nutrunners are widely used in manufacturing because of their ability to tighten threaded fasteners rapidly, their capacity to generate high torque, and their reliability in achieving target torque levels. Joint tightening is dependent on the operator's capacity to react against spindle torque, because torque can build only if there is opposing force at the handle generated by the operator, by the inertia of the tool and hand, or by an accessory such as a torque reaction bar. To ensure the quality of the operation and the safety of the operator, it is important for the operator to be able to react against reaction forces transmitted to the handle. If the building torque reaction force overpowers the operator's strength, then the tool will snap the operator's hand in the direction of the torque reaction, away from the operator (Oh & Radwin, 1997). When the operator cannot react against this torque, there may not be enough torque to fasten a joint, potentially causing a failed assembly and in some cases resulting in an accident or injury.

Forceful exertions have been related to physical stress, including fatigue and musculoskeletal disorders of the upper limb (Armstrong, Radwin, Hansen, & Kennedy, 1986; Silverstein, Fine, & Armstrong, 1987). In order to minimize operator exertions it is necessary to identify and understand the factors that influence forces acting against the operator. Several methods have been used to directly measure forces during tool operation. They include direct measurement,

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electromyography (EMG), and subjective assessment. Force or pressure sensors mounted at the point of force application (Fellows & Freivalds, 1989; Oh & Radwin, 1993; Radwin, Oh, Jensen, & Webster, 1992) involve direct force measurement but require custom sensors and tool modifications. Electromyography (Basmajian 1985; Bouisset, 1973) can be used to estimate applied hand force; however, the relationship between EMG and muscle exertions involving dynamic movement is not well understood. As an indirect measurement, subjective ratings of perceived exertion are sometimes used to identify conditions that minimize perceived force exertion level (Ulin, Snook, Armstrong, & Herrin, 1992).

Required hand force can sometimes be estimated under the assumption of static equilibrium (Radwin, VanBergeijk, & Armstrong, 1989; Radwin, Oh, & Fronczak, 1995). When considerable hand movement occurs during tool operation, the hand force estimated using static models may be less accurate because of inertial effects. In this case, a dynamic mechanical model may provide a more accurate hand force estimation. The goals of this study were to construct a simple deterministic dynamic mechanical model for estimating hand forces during power nutrunner operation and to examine how these forces vary when the tool is operated under different combinations of target torque and joint hardness.

METHODS

Dynamic Model

We developed a dynamic mechanical model for right-angle nutrunner operation in the horizontal plane in which the longitudinal axis of the tool spindle was perpendicular to the ground. The Cartesian coordinate system used was relative to the orientation of the hand and consistent with the International Standards Organization basicentric (ISO 5349, 1986) coordinates (see Figure 1). The origin (O) was arbitrarily taken as the intersection between the line passing through the longitudinal axis of the spindle and the y-z plane at the end of the socket. All dimensions were

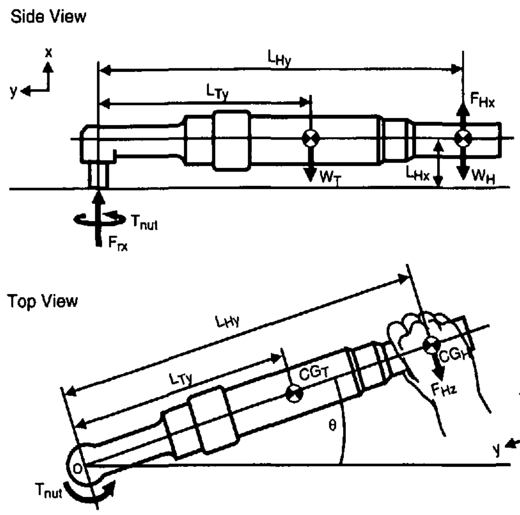

Figure 1. External coplanar forces acting on a right angle power hand tool.

measured from this origin, and moments were calculated with respect to the origin (unless otherwise specified). Torque in the clockwise direction about the spindle was defined as positive when facing the threaded fastener head.

As described by Radwin et al. (1989, 1995), under the assumption of static equilibrium, static hand reaction force at a given time can be calculated as torque at the spindle divided by the handle length:

$$F_{Hz} = \frac{T_{nut}}{L_{Hy}},$$

in which F = force, H = hand, T = torque, and L = length. Using the equations of motion, the following system of equations describe the dynamic hand forces and moments:

$$\Sigma M_z\text{: } W_T L_{Ty} + W_H L_{Hy} - F_{Hx} L_{Hy} = 0 \quad (1)$$

$$\Sigma M_x\text{: } -T_{nut} + F_{Hz} L_{Hy} = (I_{tool} + m_H L_{Hy}^2)\, \alpha_{tool}, \quad (2)$$

in which M = moment, W = weight, subscript T ($_T$) = tool, I = moment of inertia, m = mass, and α = angular acceleration. The detailed model can be found in Oh (1995). Hand reaction force (F_{Hz}) and tool support force (F_{Hx}) can be determined by solving Equation 1 and Equation 2:

$$F_{Hx} = \frac{1}{L_{Hy}} (W_T L_{Ty} + W_H L_{Hy}) \qquad (3)$$

$$F_{Hz} = \frac{1}{L_{Hy}} [(I_{tool} + m_H L_{Hy}^2)\alpha_{tool} + T_{nut}]. \qquad (4)$$

Several simplifying assumptions were made. It was assumed that forces could be summed along the handle without producing coupling moments. This assumption allowed hand force to be considered as a single point of application. The hand and lower arm mass was considered a point mass, and hand force was concentrated at the center of the grip, which coincided with the center of gravity (CG) of the hand. This assumption enabled the moment of inertia of the hand to be zero at its CG. Only hand force components reacting against torque (F_{Hz}) and supporting the tool (F_{Hx}) were considered in the model. The hand force in the y direction was assumed to be insignificant; furthermore, it was assumed that the hand does not create torque along the y axis, which means that there was no twisting motion by wrist flexion or extension during tool operation. Frictional forces were also ignored.

Equipment

Hand reaction force (F_{Hz}) during tool operation was calculated, based on the mode described in Equation 4, by substituting geometric and inertial parameters of the power hand tool studied and using kinematic data collected in a previous investigation (Oh & Radwin, in press).

A computer-controlled power hand tool was used to study hand tool operation in the laboratory. An Atlas Copco Tensor right angle nutrunner (ETV-G100-L13N-CTAD) was operated on an Indresco joint simulator. The tool contained a torque transducer and an angle encoder integrated into the spindle head, which outputted signals representing applied torque (T_{nut}) and angular spindle rotation. Specific tool parameters are listed in Table 1. A detailed description of the equipment is provided in Oh and Radwin (1997). Data for only tool operation in a horizontal workstation where the longitudinal axis of the joint head was perpendicular to the ground were used for this study.

TABLE 1

Tool Parameters

Parameter	
Tool length	58.5 cm
Spindle to center of grip length	48.0 cm
Handle circumference	11.5 cm
Weight	37 N
Free speed	220 revolutions/min
Torque range	30 to 100 Nm
Center of gravity location from the spindle[a]	21.0 cm
Tool inertia with respect to the spindle[a]	0.3003 kg/m^2

[a] Measured in the laboratory.

A Penny & Giles flexible electrogoniometer was used for measuring angular handle displacement (θ)about the spindle. Angular data were sampled using a 12-bit analog-digital converter at a sample rate of 500 Hz. First and second derivatives of θ were taken in order to calculate angular velocity and angular acceleration, respectively. A digital low-pass filter with a cutoff frequency of 55 Hz was used to reduce signal noise. The average mass of the hand and lower arm was approximated as 1.6 kg, according to Dempster (1955). The tool CG was estimated as 0.21 m measured from the tool spindle (Drillis, Schneck, & Gage, 1963). The mass moment of inertia of the tool (I_{tool}) was measured using the quick-release method (Bouisset & Pertuzon, 1968; Drillis, Contini, & Bluestein, 1964). A total of 10 trials were made to estimate I_{tool}. The average was 0.3003 kg $\cdot$ m^2 (SD = 0.0198 kg $\cdot$ m^2).

Experimental Design

The three-factor full-factorial experimental design included target torque (T), torque buildup time (B), and subject (S). Subject was considered a random variable, and torque and torque buildup time were fixed variables. All combinations of three target torques (25, 40, and 55 Nm) and five torque buildup times (35, 150, 300, 500, and 900 ms) were presented randomly to every participant. Ten replicates were made for each experimental condition, and the last five trials were used for data analysis in order to reduce learning effects. Six inexperienced volunteers (three men and three women) participated. The participants' average age was 21 years (SD = 1.5 years), average stature was 167 cm (SD = 12 cm), and average body weight was 72 kg (SD = 23 kg).

Dependent Variables

Representative torque, hand angular acceleration, and hand force records are illustrated in Figure 2. Inertial torque was calculated from angular acceleration measurements and by inertia of the tool and hand. Inertial force was defined by the ratio of inertial torque and the tool handle length (0.48 m). Peak inertial force during torque buildup in the positive direction (PIP) and after shutoff in the negative direction (PIN) were determined. Four dependent variables were measured for investigating target torque and buildup time effects on F_{Hz}, including peak force during buildup (PFP), average force during buildup (AFP), force impulse during buildup (IFP), and peak hand force after shutoff (PFS). The error between F_{Hz} estimated using the static mechanical model and the dynamic mechanical model, F_{error}, was calculated as

$$F_{error}(\%) = \frac{Hand\ Force_{static} - Hand\ Force_{dynamic}}{Hand\ Force_{static}} \times 100.$$

Repeated-measures analysis of variance (ANOVA) was used to determine statistically significant effects for hand reaction force, inertial

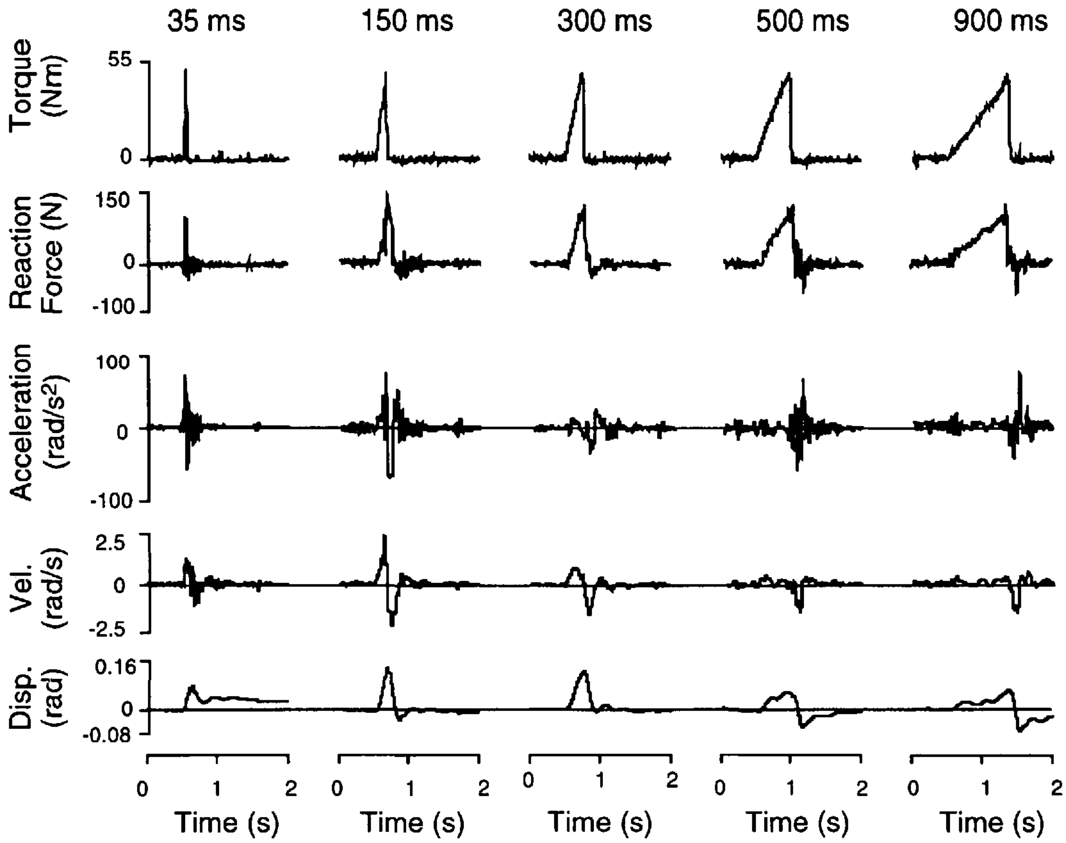

Figure 2. Representative reaction torque at the spindle, hand reaction force estimated using the dynamic model, handle acceleration, handle velocity, and handle displacement.

force, and F_{error}. Post-hoc Tukey pairwise contrast tests were used for selected significant effects. All statistical analysis was performed using BMDP statistical software.

Model Validation

The validity of the dynamic model was tested by comparing directly measured hand reaction force with the hand reaction force estimated using the model. An aluminum strain gauge dynamometer (Radwin, Masters, & Lupton, 1991) weighing 0.1 kg was rigidly attached at the end of the nutrunner handle and grasped by the operator. The addition of the dynamometer extended the distance between the hand and spindle (L_H) to 0.67 m. Ten operations were performed for both a hard joint (35-ms buildup) and a soft joint (900-ms buildup). Target torque was fixed at 55 Nm. Peak and average hand force, as well as force impulse during torque buildup, were calculated. Repeated-measures ANOVA was used to determine the significant effects of tool dynamics on hand reaction force.

RESULTS

Inertial Force from Tool and Hand Mass Moment of Inertia

The ANOVA F statistics and corresponding p values for the main and interaction effects are summarized in Table 2. Peak inertial force during torque buildup (PIP) was significantly influenced by target torque and torque buildup time. On average, PIP increased by 76% as target torque increased from 25 to 55 Nm (see Table 3). Torque buildup time and the interaction of T × B (see Figure 3) had a significant effect on PIP. A post hoc Tukey test indicated that there was a significant decrement in PIP as buildup time increased from 35 to 150 ms for all three torque levels ($p < .01$). When torque buildup time was greater than or equal to 300 ms, PIP for 40 and for 55 Nm torque did not significantly change ($p > .05$).

Target torque had a significant effect on peak inertial force after shutoff (PIN). As torque increased from 25 to 55 Nm, the magnitude of PIN increased by 89% (see Table 3). Torque buildup time also had a significant effect on PIN (see Figure 4). A Tukey pairwise test demonstrated that the magnitude of PIN was greatest for a 35-ms buildup time ($p < .01$). The T × B interaction was not statistically significant for PIN ($p > .01$).

Hand Force

Torque, buildup time, and T × B had significant effects on peak hand force (PFP), average hand force (AFP), and force impulse (IFP) during the torque buildup phase. When torque increased from 25 to 55 Nm, PFP increased by 108%, AFP increased by 103%, and IFP increased by 126% (see Table 3). Torque buildup time and T × B effects on PFP, AFP, and IFP were also significant (see Figure 3). Tukey pairwise contrasts

TABLE 2

Summary of F Statistics and p Values for Significant Main Effects and Interactions

Dependent Variable	Unit	Torque $F(2,10)$	Torque p	Build-up Time $F(4,20)$	Build-up Time p	$T \times B$ $F(8,450)$	$T \times B$ p
PIP	N	29.9	<.01	43.5	<.01	3.0	<.01
PIN	N	63.5	<.01	8.4	<.01	*ns*	*ns*
PFP	N	288.7	<.01	18.5	<.01	13.4	<.01
AFP	N	537.5	<.01	51.0	<.01	32.2	<0.01
IFP	Ns	503.0	<.01	1623.0	<.01	81.6	<.01
PFS	N	56.3	<.01	6.8	<.01	*ns*	*ns*
F_{error}	%	5.1	<.05	50.3	<.01	*ns*	*ns*

Note: Ns = newton seconds.
ns = not significant at $p < 0.05$.

TABLE 3

Summary Statistics for Significant Torque Effects (mean and *SD* in parentheses)

Dependent Variable	*Unit*	*Target Torque* 25 Nm	40 Nm	55 Nm
PIP	N	10.4 (7.3)	13.4 (9.9)	18.2 (13.2)
PIN	N	−11.9 (4.8)	−18.0 (7.7)	−23.3 (9.4)
PFP	N	57.8 (13.2)	88.3 (21.8)	120.0 (28.4)
AFP	N	24.1 (6.2)	35.4 (12.0)	49.0 (17.2)
IFP	Ns	9.9 (6.9)	16.8 (12.4)	22.4 (17.1)
PFS	N	31.0 (12.5)	41.8 (20.7)	53.6 (23.1)
F_{error}	%	20.1 (14.5)	16.5 (12.7)	16.1 (12.4)

Note: NS = newton seconds

demonstrated that PFP was significantly greater for the 150-ms buildup time ($p < .01$). PFP did not significantly differ for buildup times 300 ms or greater for all three torque levels ($p > .05$). PFP was significantly less ($p < .05$) for the 35-ms buildup time than for the other buildup times when target torque was 40 and 55 Nm. AFP increased significantly as buildup time increased from 35 to 150 ms ($p < .01$) for all three torque levels (see Figure 3). AFP remained relatively constant for the buildup times 300 ms or greater ($p < .01$) for all torque levels. Furthermore, AFP was not significantly affected by target torque for the 35-ms buildup time ($p > .1$). IFP was least for

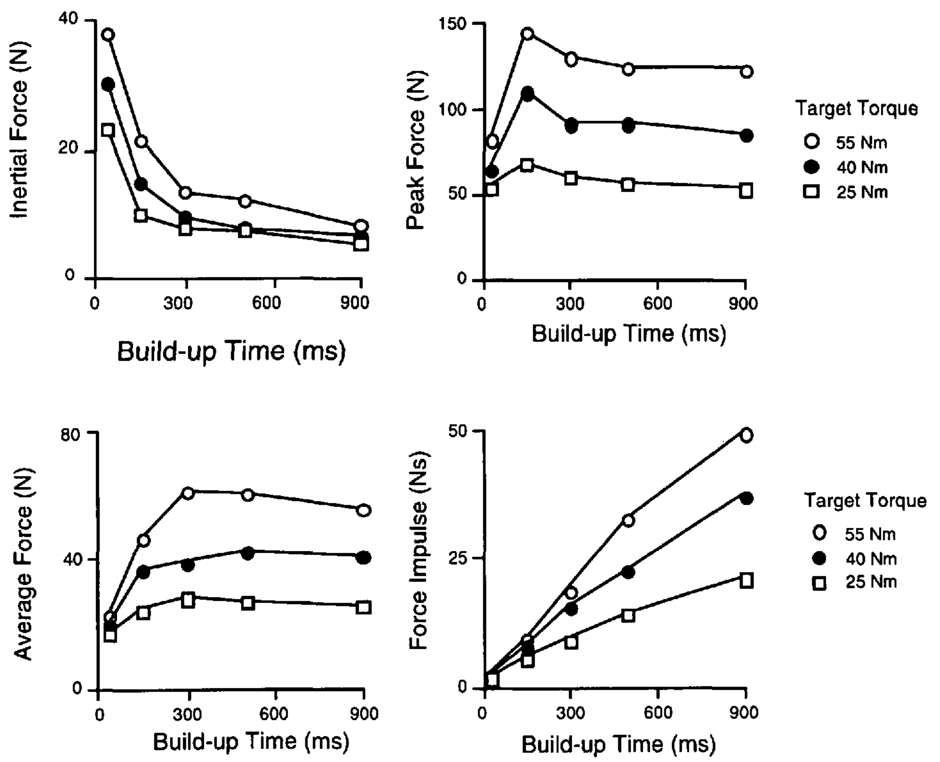

Figure 3. Significant torque and buildup time interaction for peak inertial force, peak hand force, average hand force, and force impulse during torque buildup.

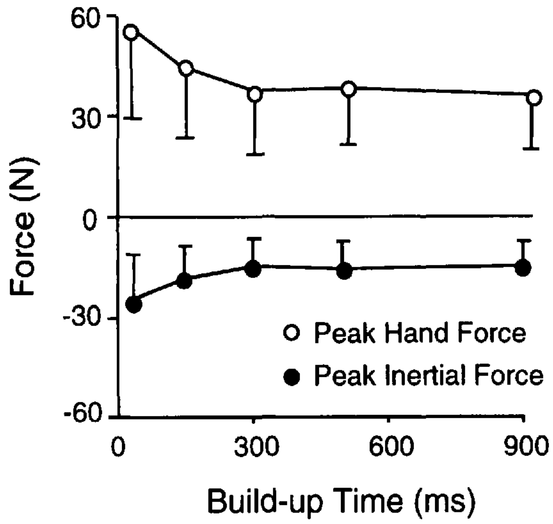

Figure 4. Peak inertial force and peak hand force after shutoff were influenced by buildup time. As buildup time increased from 35 to 150 ms, the magnitude of PIN and PFS decreased (error bars represent one standard deviation).

the 35-ms buildup time and greatest for the 900-ms buildup time for all three torque levels ($p < .01$).

PFS was significantly affected by torque and torque buildup time. As torque increased from 25 to 55 Nm, PFS increased by 73% (Table 2). A Tukey pairwise contrast test showed that PFS for the 35-ms buildup time was significantly greater ($p < .01$) than PFS for other buildup times (see Figure 4).

Static Model versus Dynamic Model

F_{error} was significantly affected by torque and buildup time. As torque increased from 25 to 55 Nm, F_{error} decreased by 25% (see Table 3). The post hoc Tukey pairwise contrast test showed that F_{error} was greatest for the 35-ms buildup time, followed by F_{error} for the 150-ms buildup time ($p < .05$; see Figure 5).

Model Validation

Peak hand force, $F(1, 5) = 485, p < .01$, average hand force, $F(1, 5) = 898, p < .01$, and impulse $F(1, 5) = 3030, p < .01$, measured at the handle were significantly greater for the 900-ms buildup time (soft joint) than for the 35-ms buildup time (hard joint; see Figure 6). Similarly, peak dynamic hand force, $F(1, 5) = 254, p < .01$, average dynamic hand force, $F(1, 5) = 228, p < .01$, and dynamic impulse, $F(1, 5) = 3854, p < .01$, were greater for the soft joint than for the hard joint. Peak hand force estimated for the static model was significantly greater than for the dynamic model, $F(1, 9) = 165, p < .01$, or for measured hand force $F(1, 9) = 731, p < .01$. Average peak static hand force was 13% greater than dynamic peak hand force and 26% greater than measured hand force. The dynamic model overestimated peak hand force, $F(1, 9) = 181, p < .01$, by 15.7 N (SD = 2.7 N) for the hard joint and by 4.7 N (SD = 3.6 N) for the soft joint. Force impulse, $t(19) = -1.9, p > .05$, and average force, $t(19) = -1.9, p > .05$, were not significantly different whether measured directly or estimated using the dynamic model.

DISCUSSION

This study demonstrates that a simple dynamic mechanical model can be used for estimating hand force during right-angle nutrunner operation and that the estimated hand force was affected by tool dynamics parameters, including target torque and buildup time. Estimated peak and average hand force (PFP and AFP) were less

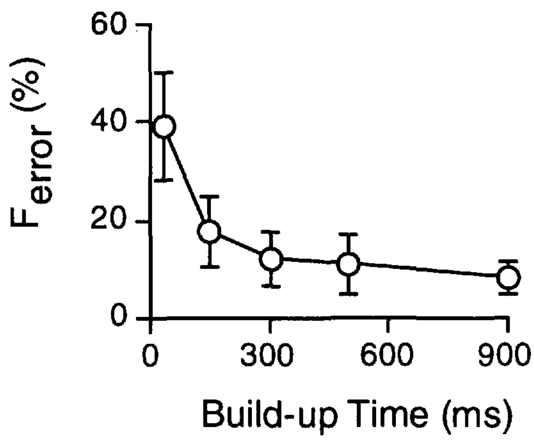

Figure 5. Significant buildup time effect on the difference between the hand force estimated using the dynamic model and the hand force estimated under the assumption of static equilibrium.

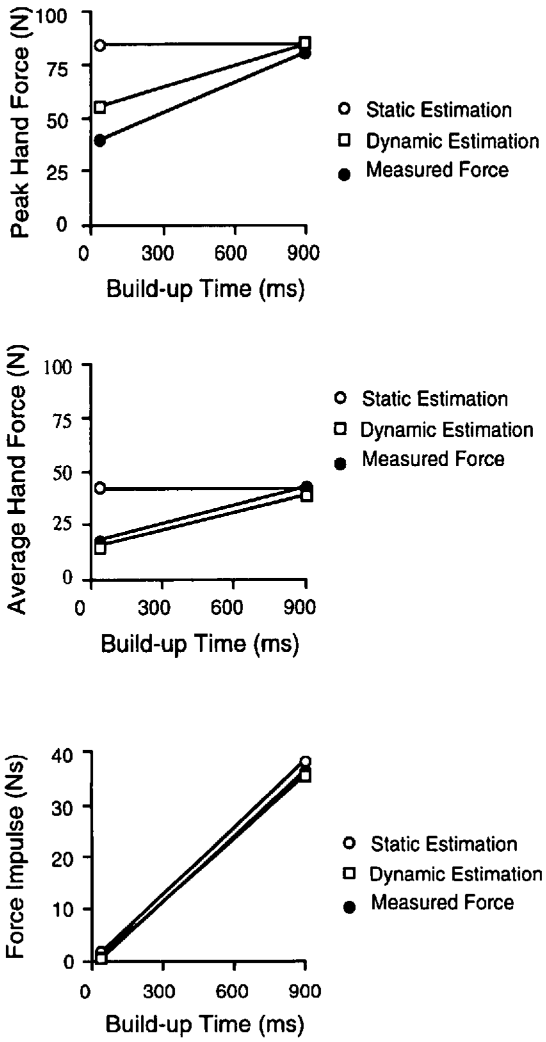

Figure 6. Peak hand force, average hand force, and force impulse measured directly and estimated by the static and dynamic models.

for the smaller target torque (25 Nm) and for hard joints (35-ms buildup time). Both PFP and AFP increased markedly as buildup time increased from 35 to 150 ms.

Inertial effects should be considered when motion is involved. The estimated hand force using the dynamic model was 60% to 90% of the estimated hand force for the static model, depending on the buildup time. The static model did not account for the effect of torque rate and buildup time, which had a significant effect on estimated hand force (see Figure 3). Another limitation of the static model was that it could not estimate force acting on the hand after tool shutoff. Considerable hand force was observed after tool shutoff (see Figure 4).

It was anticipated that the greater the tool inertia, the more reaction torque it is capable of absorbing. Ignoring the hand and arm, the moment at the spindle, $M_o(t)$, is equal to the inertia of the tool with respect to the spindle multiplied by the tool angular acceleration:

$$M_o(t) = I_{tool}\alpha(t).$$

Given that torque builds up linearly with respect to time, the moment at the spindle can be expressed as

$$M_o(t) = ct = I_{tool}\alpha(t), \tag{5}$$

for which c is the torque buildup rate (in newton meters per second), and t is time (in seconds). For any given target torque, c is greater for short

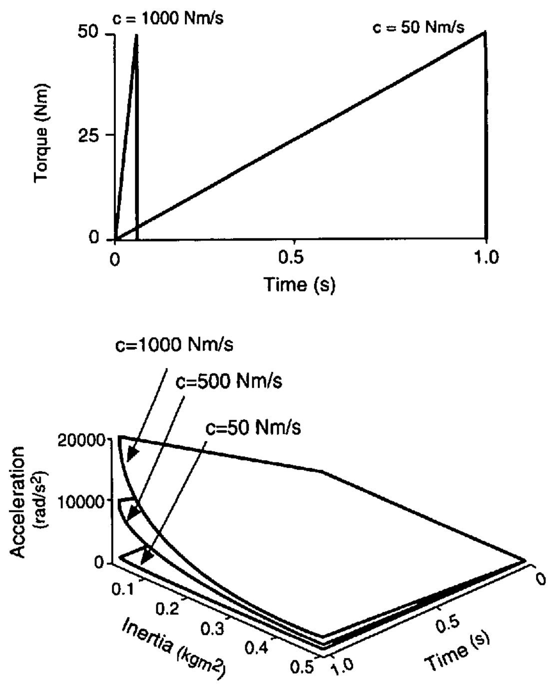

Figure 7. Top: The rate of torque buildup is determined by the ratio between the target torque and the time required to achieve target torque. Bottom: The effect of inertia, torque buildup rate, and torque buildup time on the handle angular acceleration.

torque buildup times and less for long torque buildup times (see Figure 7). Equation 5 can be written in terms of tool acceleration as

$$\alpha(t) = \frac{ct}{I_{\text{tool}}} \tag{6}$$

Equation 6 shows that tool acceleration is inversely proportional to the tool inertia and is proportional to c and t (see Figure 7).

Increasing the inertia of the tool results in less angular acceleration, but increasing the tool inertia by augmenting its mass gives rise to a trade-off. When the tool inertia was less than 0.3 $kg \cdot m^2$, angular acceleration was substantially lessened by increasing its inertia, but when the tool inertia was greater than 0.3 $kg \cdot m^2$, increased inertia did not result in a significant reduction in angular acceleration (see Figure 7). Even if substantial angular acceleration is reduced, adding tool mass increases the static tool support force requirement (see Equation 3).

The hand force estimate in Equation 4 required an estimation of hand and arm mass. In order to simplify the model, we assumed that only the mass of the hand and forearm acted on the tool and that the CG of the hand and forearm coincided with the center of the grip. Although the dynamic model included inertial effects of the tool, hand, and forearm, the validation study showed that inertial effects were somewhat underestimated, resulting in slightly greater peak hand force estimates using the dynamic model. Parts of the upper arm and body mass should also contribute to the mass acting on the tool; this contribution depends on the posture and position of the operator. Future models should account for force components affected by operator posture and orientation with respect to the tool.

Equation 6 shows that angular acceleration increases as torque buildup rate increases. Longer torque buildup times resulted in less acceleration. This may explain why inertial force, which is proportional to hand acceleration, was greater for the 35-ms buildup time. A previous study (Oh & Radwin, in press) observed that greater peak handle velocities and accelerations were associated with the 35-ms buildup time, whereas less handle displacement occurred under identical experimental conditions. Because handle acceleration and velocity associated with soft joints were less than that for hard joints (Oh & Radwin, in press), the inertial force provided by the tool decreased, requiring greater hand force.

The 35-ms buildup time may have some advantage over longer torque buildup times. Greater handle acceleration increases the inertial contribution for absorbing torque reaction force (see Figure 3). Consequently, the operator exerts less hand force during torque buildup. In addition, operator capacity to react against tool forces is enhanced by increased maximum voluntary contraction when eccentric hand velocity increases (Hortobagyi & Katch, 1990; Oh & Radwin, 1997); however, the health consequences of eccentric contraction are not known. Although hand reaction force was less for a hard joint, greater peak torque variance was associated with hard joints (Oh & Radwin, in press). A joint could be "softened" by slowing the power hand tool spindle speed in order to improve torque accuracy at a trade-off of increased hand force.

Oh and Radwin (in press) observed that medium-hardness joints were related to greater handle instability as well as greater muscular contraction for the same tool as in the current study. Because the tool angular acceleration associated with the medium joints decreased significantly as buildup time increased from 35 to 150 ms, the model predicted that the hand force would be greater for the 150-ms buildup time and the same target torque. The joint considered "hard" (500-ms torque buildup time) in Radwin et al. (1989) was in fact a medium-hardness joint, which may explain why greater exertions were observed for a "hard" joint than for a soft joint (2-s torque buildup time, which is contrary to the current study findings).

Oh and Radwin (in press) observed from forearm muscle EMG latency that contraction for medium joints was not initiated until 64% of the target torque had already built up. Consequently, the greater handle instability observed for medium joints could be related to an absence of the benefit of early muscle contractions for controlling the tool, in addition to decreased inertial force, as evidenced in the current study. The greater instability for medium-hardness joints might also be attributable to a theorized mechanical resonance that amplifies hand motion (velocity and displacement) in the tool-operator system resulting in greater handle instability (as proposed by Lindqvist, 1993).

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REFERENCES

Armstrong, T. J., Radwin, R. G., Hansen, D. J., & Kennedy, K. W. (1986). Repetitive trauma disorders: Job evaluation and design. *Human Factors, 28,* 325–336.

Basmajian, J. V. (1985). *Muscles alive: Their functions revealed by electromyography* (5th ed.). Baltimore: Williams & Wilkins.

Bouisset, S., & Pertuzon, E. (1968). Experimental determination of the moment of inertia of limb segment. In J. Wartenweiler, E. Jokl, & M. Hebbelinck (Eds.), *Biomechanics I* (pp. 106–109). New York: Karger.

Bouisset, S. (1973). EMG and muscle force in normal motor activities. *New Developments in Electromyography and Clinical Neurophysiology, 1,* 547–583.

Dempster, W. T. (1955). *Space requirements of the seated operator* (Tech. Report WADC-TR-55-159). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratories.

Drillis, R., Schneck, D., & Gage, H. (1963). The theory of striking tools. *Human Factors, 5,* 467–478.

Drillis, R., Contini, R., & Bluestein, M. (1964). Body segments parameters: A survey of measurement technique. *Artificial Limbs, 8,* 44–66.

Fellows, G. L., & Freivalds, A. (1989). The use of force sensing resistors in ergonomic tool design. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 713–717). Santa Monica, CA: Human Factors and Ergonomics Society.

Hortobagyi, T. & Katch, F. I. (1990). Eccentric and concentric torque-velocity relationships during arm flexion and extension: Influence of strength level. *European Journal of Applied Physiology, 60,* 395–401.

International Standards Organization. (1986). *Mechanical vibration—Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration* (ISO 5349-1986). New York: Author.

Lindqvist, B. (1993). Torque reaction force reaction in angled nutrunners. *Applied Ergonomics, 24,* 174–180.

Oh, S. (1995). *Tool dynamics and workstation effects on power hand tool operation.* Unpublished doctoral dissertation, University of Wisconsin-Madison, Madison, WI.

Oh, S., & Radwin, R. G. (in press). The influence of target torque and torque build-up time on physical stress in right angle nutrunner operation. *Ergonomics.*

Oh, S., & Radwin, R. G. (1993). Pistol grip power tool handle and trigger size effects on grip exertions and operator preference. *Human Factors, 35,* 551–569.

Oh, S., & Radwin, R. G. (1997). The effects of power hand tool dynamics and workstation design on handle kinematics and muscle activity. *International Journal of Industrial Ergonomics, 20*(1), 59–74.

Radwin, R. G., Masters, G. P., & Lupton, F. W. (1991). A linear force-summing hand dynamometer independent on point of application. *Applied Ergonomics, 22,* 339–345.

Radwin, R. G., Oh, S., & Fronczak, F. J. (1995). A mechanical model of hand force in power hand tool operation. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 548–552). Santa Monica, CA: Human Factors and Ergonomics Society.

Radwin, R. G., Oh, S., Jensen, T. R., & Webster, J. G. (1992). External finger forces in submaximal five-finger static pinch prehension, *Ergonomics, 35,* 275–288.

Radwin, R. G., VanBergeijk, E., & Armstrong, T. J. (1989). Muscle response to pneumatic hand tool torque reaction force reaction forces. *Ergonomics, 32,* 655–673.

Silverstein, B. A., Fine, L., & Armstrong, T. J. (1987). Occupational factors and carpal tunnel syndrome. *American Journal of Industrial Medicine, 11,* 343–358.

Ulin, S. S., Snook, S. H., Armstrong, T. J., & Herrin, G. D. (1992). Preferred tool shapes for various horizontal and vertical work locations. *Applied Occupational and Environmental Hygiene, 7,* 327–337.

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